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Comparative Analysis of PBR and NPR: Technical Pathways, Resource Investment and Applicability

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Abstract:

Physically Based Rendering (PBR) and Non-Photorealistic Rendering (NPR) represent the two main development paths in computer graphics. PBR emphasizes physical realism and has become the standard in film and large-scale games, while NPR highlights stylized expression and is commonly found in animation and indie works. For low-budget production teams, finding a balance between visual effects and resource costs is a key issue. This paper provides a comprehensive review of typical research and applications of photorealistic rendering (PBR) and Non-Photorealistic Rendering (NPR) based on a systematic survey of relevant literature. The study starts from the technical approach, analyzing the differences between the two in rendering principles and implementation methods. At the same time, from the perspective of computing and production cost analysis, compare its input requirements in terms of hardware computing power, asset creation, labor costs, and development cycle. Finally, combining practical application scenarios such as films, games, and animation, the paper explore their applicability and limitations in different types of works. Building on this foundation, this paper further draws on existing academic research and industry case studies to summarize the respective strengths and weaknesses of the two approaches, and proposes reasonable selection strategies under low-cost constraints, with the aim of providing references for future research and practical production.

Keywords: Physically Based Rendering; Non-Photorealistic Rendering; Comparison of Rendering Techniques; Low-Budget Production.

1. Introduction

Rendering technology is an important research direction in computer graphics, aimed at transforming three-dimensional scenes into visually expressive two-dimensional images. With the development of research, two main paths have gradually formed: Physically Based Rendering (PBR) and Non-Photorealistic Rendering (NPR) These two methods not only reflect differences in technical paradigms, but also indicate the industry‘s distinct pursuits of realism and stylization.

The theoretical foundation of PBR can be traced back to the microfacet reflection model proposed by Cook and Torrance, which was the first to introduce physical laws into computer graphics and established a solid framework for realistic rendering [1]. Subsequently, the rendering equation proposed by *Kajiya* further unified the model of light propagation, providing a theoretical framework for photorealistic rendering [2]. With these theoretical foundations established, subsequent advancements emphasized material modeling, global illumination, and energy conservation, facilitating the widespread application of PBR across academic and industrial domains. Nowadays, PBR has become the de facto standard in the film industry and AAA games. By standardizing the BRDF (Bidirectional Reflectance Distribution Function) and a unified set of material parameters, it allows different platforms, engines, and production workflows to seamlessly integrate, greatly improving the efficiency of photorealistic rendering.

In contrast, the goal of NPR is not to reproduce reality, but to enhance visual expression through artistic and stylized methods. The cool-to-warm shading model proposed by Gooch et al. is an early representative method of NPR. By simplifying the representation of lighting and color, it enhances shape readability and highlights artistic effects [3]. Afterwards, Hertzmann‘s proposed ‚image analogy‘ method combined image processing with style transfer, expanding the applications of NPR and enabling it to mimic the brushstrokes and artistic styles of different artists [4]. In recent years, surveys have further provided a systematic classification of NPR methods, including contour extraction, stroke simulation, color layering, and deep learning-driven style transfer, thereby offering a clear developmental roadmap for subsequent research [5]. Meanwhile, recent surveys on neural style transfer indicate that this approach can achieve richer artistic expressiveness while maintaining real-time performance, and is gradually expanding into domains such as games, animation, and interactive applications [6].

PBR, known for its high realism and consistency, is widely used in movies, games, and virtual reality, making it a key technology for immersive experiences. However, its high computational and resource demands are often difficult for small teams to afford. In contrast, NPR emphasizes low cost and stylization, making it particularly advantageous in animation and independent works.

With the development of neural rendering and hybrid rendering, the boundary between the two is gradually becoming blurred. The PBR framework can incorporate NPR modules to balance realism and artistry, while the physical consistency of PBR can also enhance the stability of NPR [7]. These cross-disciplinary studies indicate that rendering approaches will tend to diversify, but budget and audience remain key factors in actual choices.

In this context, this paper aims to provide a systematic review and comparison of PBR and NPR. The study is conducted from three dimensions: technical approaches, computational and production cost analysis, and application scenarios. It analyzes the differences between the two in lighting modeling, computational overhead, artistic requirements, and practical applicability, summarizing their advantages and limitations. Further combining literature and industry cases, the paper proposes selection recommendations under low-budget conditions, providing reference for research and practice.

2. Rendering Principles and Expressiveness

The core idea of PBR is to follow the laws of optics as closely as possible, achieving visual effects close to the real world through precise modelling of lighting and materials. Its development typically traces back to the microfacet reflection model proposed by Cook and Torrance, which provides a physical basis for photorealistic rendering [1]. Later, Disney‘s proposed Principled BRDF model transformed complex physical calculations into a more manageable material parameter system, allowing PBR to rapidly spread in the film and game industries and become the de facto standard [8]. In recent years, researchers have begun attempting to combine PBR with neural rendering. For example, the PBR-NeRF framework proposed by Zhang et al. can improve the efficiency of geometry and lighting estimation while maintaining realism [9]. Li et al.‘s TexGaussian demonstrates the potential of generating textures from point clouds [10]. These explorations indicate that PBR is gradually moving towards automation and efficiency while maintaining physical accuracy.

In contrast, NPR does not pursue strict physical accuracy, but emphasises artistic and stylised visual expression. It often enhances expressiveness by exaggerating physical features, emphasising contour lines, or adjusting colour relationships. Early representative methods include the

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colour illumination model proposed by Gooch et al, which expresses structural information through warm and cool tones while avoiding complex physical calculations [3]. And the Suggestive Contours proposed by DeCarlo et al, this method uses additional contour lines to enhance shape perception [11]. With the development of deep learning and neural rendering, NPR has gradually entered the stage of continuous 3D stylisation. For example, the Ref-NPR model proposed by Yang et al. combines reference images with neural radiance fields to achieve consistent style expression under multi-view conditions [12]. Such new methods indicate that NPR is no longer limited to ‚cartoonisation' or ‚line drawing', but is evolving towards more flexible and automated style transfer.

3. Calculation and Production Cost Analysis

3.1 Physical accuracy

PBR is characterised by strict adherence to energy conservation and the rendering equation, with core models such as Cook–Torrance BRDF and Disney's Principled BRDF maintaining consistency and physical plausibility under different lighting conditions [1, 8]. These types of models usually include precise descriptions of microfacet distribution, Fresnel reflection and geometric occlusion.

The NPR method does not emphasise physical accuracy and often achieves a stylised effect through heuristic rules. For example, the lighting model proposed by Gooch et al. uses the contrast of warm and cool colours to convey shape information, whereas DeCarlo et al.'s Suggestive Contours improves shape perception through contour enhancement [3, 11]. These methods may deviate from the real physical laws in terms of expressive effect, but the calculation is lighter. Complexity of material and lighting modelling. These parameters make the material highly controllable, but they also increase production difficulty and computational overhead.

3.2 Complexity of material and lighting modelling

The PBR material system is usually quite complex. Disney's Principled BRDF includes at least 12 control parameters, such as roughness, metallic, IOR, and subsurface scattering [8]. These parameters make the material highly controllable, but they also increase production difficulty and computational overhead.

NPR models usually use fewer parameters. For example, Toon Shading is often completed using 2–4 thresholds and colour mapping to achieve material representation, significantly reducing data requirements during modelling and rendering [3]. This difference reflects the trade-off between modelling accuracy and operational complexity in the two methods.

3.3 Computational complexity

The computational load of PBR mainly depends on ray sampling and material calculations. Computation. Global illumination based on path tracing often requires minutes per frame for rendering [13]. Even with GPU acceleration and RTX ray tracing technology, real-time rendering usually requires maintaining 16–33 ms per frame on high-end GPUs [14].

In contrast, NPR has lower computational complexity. Common edge detection or toon shading rendering only requires pixel-level function mapping, usually completing a frame in less than 5 ms and achieving 30–60 FPS in real-time performance on mobile devices [15]. This performance difference is particularly noticeable under conditions of limited hardware resources.

3.4 Data dependency and production processes

PBR is highly dependent on external data in the production process. For example, HDR environment maps often exceed tens of MBs, and high-precision PBR material texture atlases can even reach hundreds of MBs [13]. Such data usually requires professional equipment to capture or relies on large commercial material libraries.

The NPR method has relatively relaxed requirements for input data. Many stylised renderings only need a simple ramp texture (<1 MB), and style transfer can even be driven by reference images [12]. Therefore, its production process leans more towards artistic design rather than high-precision physical measurement.

4. User perception and application scenarios

In addition to computation and resource investment, user perception studies and industry cases also provide an objective basis for comparing rendering methods. Relevant research usually explores dimensions such as immersion, shape recognition accuracy, and aesthetic preference, supplemented by analyses of specific application cases.

4.1 Sense of immersion and realism

In terms of immersion, the advantage of PBR lies in the realistic reproduction of the interaction between light and materials. The night scenes of Pandora in *Avatar* are a typical example: the subsurface scattering of bioluminescent plants and Na'vi skin, combined with global illumination

simulation, allows the audience to perceive a natural translucency even in dim environments [8, 13]. The manifestation of this microscopic physical effect gives virtual environments credibility, thereby significantly enhancing immersion.

Avengers: Endgame demonstrates another type of application. The reflective performance of Iron Man‘s armour and Thanos‘ weapons under explosive fire and energy impact relies on consistent definitions of the metalness and roughness parameters in PBR [8, 13]. This ensures that whether in live-action footage or post-production effects, the lighting response of the metal surfaces remains physically plausible. As a result, the virtual effects naturally blend with the live-action shots, and the audience will not be distracted by inconsistent lighting.

However, immersion is not the same as realism. Experimental studies show that most subjects prefer PBR images in terms of immersion ratings, considering them more credible [16]. However, the success of Journey demonstrates that even without complex optical simulation, stylised aesthetics can provide an equally profound immersive experience [17]. The work enhances character clarity in a desert setting through colour gradients and contour definition. This approach focuses the player‘s attention on emotion and narrative rather than physical accuracy, illustrating that the essence of immersion lies in the harmony between visual presentation and storytelling atmosphere.

4.2 Shape recognition and perception accuracy

When perceiving the shape of objects, users do not rely entirely on physical reality. Research by Cole et al. shows that line drawings and photorealistic renderings have little difference in recognition accuracy, both exceeding 90% [16]. This suggests that in conveying form, NPR and PBR may achieve similar effects.

The Legend of Zelda: Breath of the Wild exemplifies this well. Its toon shading technique uses distinct colour blocks to keep distant mountains and nearby characters visually distinct in a complex open world [18]. Players can quickly understand the environmental structure without relying on precise lighting calculations, enhancing interactive efficiency.

Another example is „Journey“, which uses colour gradients and contour enhancement in desert scenes, ensuring that the player‘s character stands out against a monochromatic background [17]. This type of stylised processing aligns with the goals of the Gooch lighting model and Suggestive Contours: to enhance perception through emphasising geometric features rather than reproducing physical reality [3, 11]. Therefore, in shape recognition tasks, NPR is not inferior to PBR and can even be more efficient in certain scenarios.

4.3 Aesthetic and style preferences

Aesthetically, NPR demonstrates a high adaptability to diverse narratives and artistic styles. Spider-Man: Into the Spider-Verse uses NPR techniques to simulate comic book outlines, spray-paint textures, and colour layering, allowing characters of different styles (such as hand-drawn, black-and-white, cyberpunk) to coexist on the same screen [19]. This highly dynamic artistic style not only becomes an important narrative tool but also lets the audience experience the unique feeling of ‚comics coming to life on the screen‘.

Hades showcases another advantage of NPR in games [20]. Its hand-drawn particle effects and layered colour flames render dungeon battles into a ‚hellish aesthetic‘ full of comic tension. This choice not only reduces resource consumption but also gives the work a distinctive artistic identity in the indie game market.

In contrast, PBR is indispensable in films and AAA games that require high realism, as it ensures the audience perceives the world as „credible.“ However, in works that emphasise narrative atmosphere and artistic differentiation, NPR offers more flexible expressiveness. In summary, aesthetic preference is not solely determined by realism, but is closely related to the stylistic intentions and emotional goals of the work.

5. Discussion

In the previous analysis, physically based rendering (PBR) and non-photorealistic rendering (NPR) exhibit significant differences in principles, resource efficiency, and user perception. However, further discussion shows that both still face several challenges in practical applications and future development, while also demonstrating potential for integration and evolution.

5.1 Current challenges and limitations

The main challenges of PBR lie in computational cost and data dependency. Although the improvement in GPU performance and the application of RTX ray tracing technology have significantly reduced rendering time, minute-level single-frame path tracing still struggles to meet real-time rendering requirements [13, 14]. In addition, high-precision material textures and HDR environment data place high demands on storage and production workflows, which is particularly burdensome for small teams.

In contrast, NPR is lighter in terms of computational and data requirements, but it often faces issues with stability

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and consistency when handling complex scenarios. For example, under multi-view conditions, maintaining a consistent stylised effect is challenging, and animation and game production usually require considerable manual correction to ensure visual coherence [12].

From the user‘s perception, although PBR has obvious advantages in immersion and realism, it has certain limitations in style expression; NPR, on the other hand, is more flexible in shape perception and artistic expression but is often considered to lack ‚credibility‘. Moreover, the boundaries between the two in industrial applications are not absolute, with some film and television works beginning to explore hybrid rendering approaches, introducing NPR style modules within the PBR framework to achieve compatibility between realism and artistic expression. The future development trend of rendering is mainly reflected in two directions. On one hand, PBR will continue to benefit from hardware iterations and the introduction of neural methods.

5.2 Future Prospects and Strategies

The future development trend of rendering is mainly reflected in two directions. On one hand, PBR will continue to benefit from hardware iterations and the introduction of neural methods. Recent studies such as PBR-NeRF integrate physical priors into neural radiance fields, achieving breakthroughs in geometry, material and lighting estimation, demonstrating the potential for automated material generation and efficient rendering [9]. At the same time, new scene representation methods like 3D Gaussian Splatting provide new solutions for real-time rendering, and are expected to become a common acceleration framework for PBR and NPR [21].

On the other hand, the development of NPR is rapidly integrating with AI technology. Chen and others, in their review system published in IJCV, summarised the latest advances in 3D Neural Stylization, pointing out that style consistency, controllability, and multi-view stability are the core challenges of NPR [22]. This means that in the future, NPR will no longer be limited to two-dimensional ‚cartoon-like‘ styles, but will expand to more complex and automated three-dimensional style expressions.

In practical applications, budget and objectives remain important criteria for selecting rendering methods. High-budget projects are more suitable for PBR to pursue ultimate realism, while low-budget teams tend to opt for NPR to achieve a distinctive style at lower costs. However, this does not mean that the two are entirely distinct. With the improvement of hardware performance and the maturation of neural rendering, the threshold for PBR is gradually lowering, while the controllability of NPR in style editing and consistency is also increasing. In the future, the two will appear more in a complementary and integrated manner, providing more flexible solutions for teams of different sizes.

6. Conclusion

In terms of technical approach, PBR achieves highly realistic lighting and material representation by strictly adhering to physical laws and a unified material system, serving as a core support for the film industry and AAA games. However, this advantage comes with high computational and resource demands. NPR aims for artistic and stylized effects, relying on simplified modeling and computational rules. It can achieve striking visual styles under limited conditions, making it particularly suitable for animation and independent works. The two form a stark contrast in terms of modeling complexity, computational burden, and data dependence.

In terms of user perception, PBR can significantly enhance immersion and realism, but research shows that NPR is also competitive in the effectiveness of shape recognition and visual expression, and stylized expression can provide a diverse aesthetic experience. Industry cases further illustrate that audience acceptance depends not only on the level of realism but also closely on the narrative atmosphere and artistic style.

Based on existing research and industry practice, the following conclusions can be drawn. PBR is more suitable for high-budget projects that pursue extreme realism, while NPR demonstrates unique value in low-budget and creativity-driven productions. However, the two are not opposed, but complementary technological paths. With the application of hardware optimization and neural rendering methods, the cost of PBR is expected to continue decreasing. Meanwhile, NPR will achieve breakthroughs in AI-driven style consistency and controllability. The future rendering landscape will exhibit diversified development, with realism, stylization, and hybrid rendering coexisting in parallel, collectively driving the enhancement of visual expressiveness.

Therefore, the choice of rendering technology should be balanced with considerations of budget, target audience, and artistic objectives. In both academic research and industry practice, the integration and complementarity of PBR and NPR will become an important trend, opening up richer possibilities for animation, games, and virtual reality.

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